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PROGRESS IN SEPARATING PLASTIC MATERIALS FOR RECYCLING

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In order to deal with the problems facing the plastics processing industry research, work is focused primarily on designing, developing and testing a variety of separation and sorting techniques able to recover plastics from wastes, which can be re-used or re-processed to form new products. In this regard, technologies developed in mineral processing can be of great help. Various techniques for separating plastics materials have been recently developed. These techniques can be divided in two main categories, i.e. wet separating techniques and dry separating techniques. This paper presents the recent progress in separating plastics reviewing the potential of the available techniques.

Keywords: Plastic separation; Sink–float separation; Flotation; Air table; Triboelectric separator

1. INTRODUCTION

Nowadays, the world is moving steadily into the age of conservation with recycling as an integral part. Recycling is an old concept but only truly came into its own with the advent of the industrial revolution. Without recycling, the life circle of products merely becomes a series of events without a logical solution to the resource conservation, since the potentially useful materials can consequently become a hazard to environment.

According to the Plastic Waste Management Institute of Japan [1], in 2002, the amount of plastic products consumption in Japan reached about 1.09×10^7 tonnes/year after running at about 1.00×10^7 tonnes/year from 1990 on. In relation to this, the total amount of plastic waste discharge was about 0.56×10^7 tonnes in 1990 rising to about 0.99×10^7 tonnes in 2000 (Fig. 1). However, only about 50 wt% of this discharged amount is reused for material recycling chemical recycling and energy recovery [1]. Waste plastics are consequently one of the main polluters, as they constitute 14.2% in weight (Fig. 2) or 46.5% in volume (Fig. 3) of Japanese municipal solid waste, (MSW) [2].

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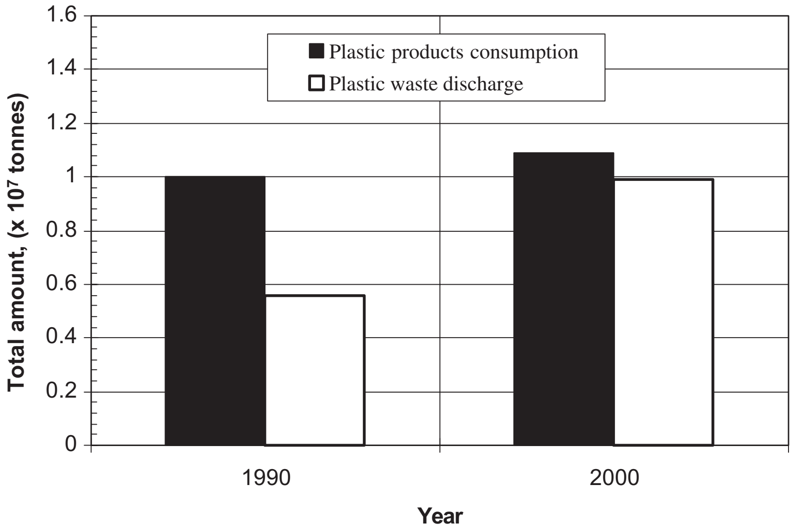

FIGURE 1 Consumed and discharged amounts of plastic materials in Japan.

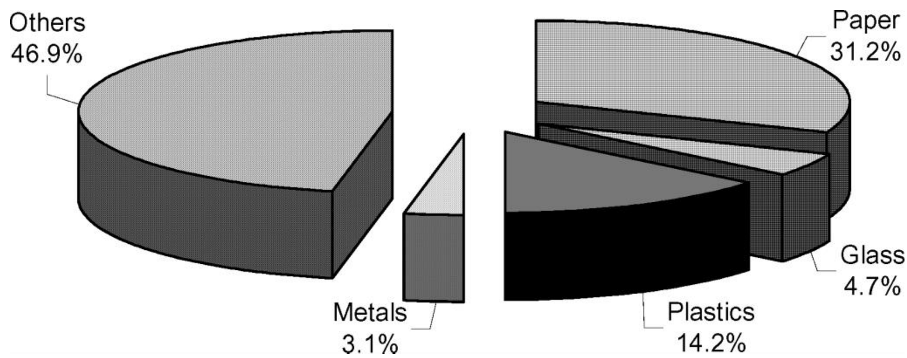

FIGURE 2 Breakdown (wt %) of MSW in Japan (FY 2002).

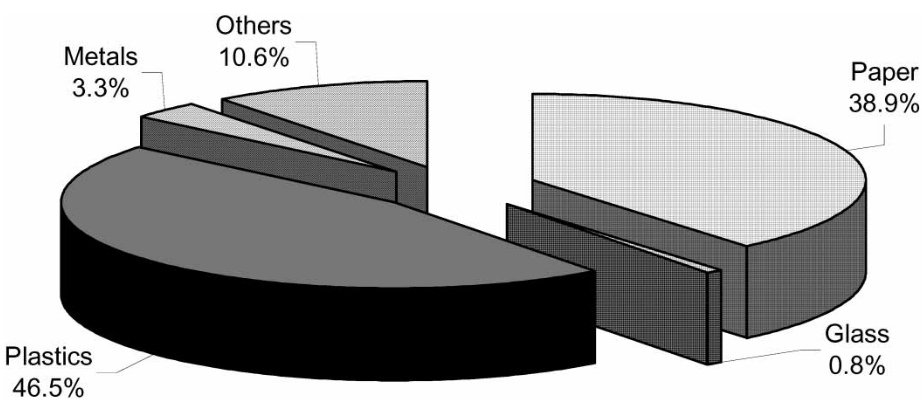

FIGURE 3 Breakdown (vol. %) of MSW in Japan (FY 2002).

TABLE I Utilization of various kinds of plastics.

Type of resin	*Utilization*
Acrylonitrile–butadiene–styrene (ABS)	Has been mass-produced since 1960s. It is used in electronic housings, telephone components, pipes and fittings, computer housings (electroplated on the inside), as well as automobile interior and exterior trim.
Polyethylene terephthalate (PET)	Developed in 1941. It is a very good material for carbonated beverage applications and other food containers. PET also finds applications in such diverse end-uses as fibres for clothing and carpets, bottles, food containers and engineering plastics for precision-moulded parts.
Polystyrene (PS)	Has been mass-produced since 1930. It is used for inexpensive packaging materials, pens, safety razors, electrical or electronic uses, building or construction, flatware and jewel boxes. PS is also used extensively in take-out restaurants for its lightweight, stiffness and excellent thermal insulation.
Polyethylene (PE)	Has been mass-produced since 1939. It is the largest volume commodity plastic. PE is used in blow-moulded beverage bottles, gas tanks, toys, fibres for clothing, etc.
Polypropylene (PP)	Has been mass-produced since the 1950s. It has excellent resistance to water, salt and acid solutions that are destructive to metals. Typical applications include ketchup bottles, yogurt containers, medicine bottles, medical syringes, beakers, automobile battery casings and carpeting markets.
Polyvinyl chloride (PVC)	Has been mass-produced since 1938. It is used in pipes and fittings, wire and cable insulation, packaging, medical applications, electrical or electronic uses, etc.

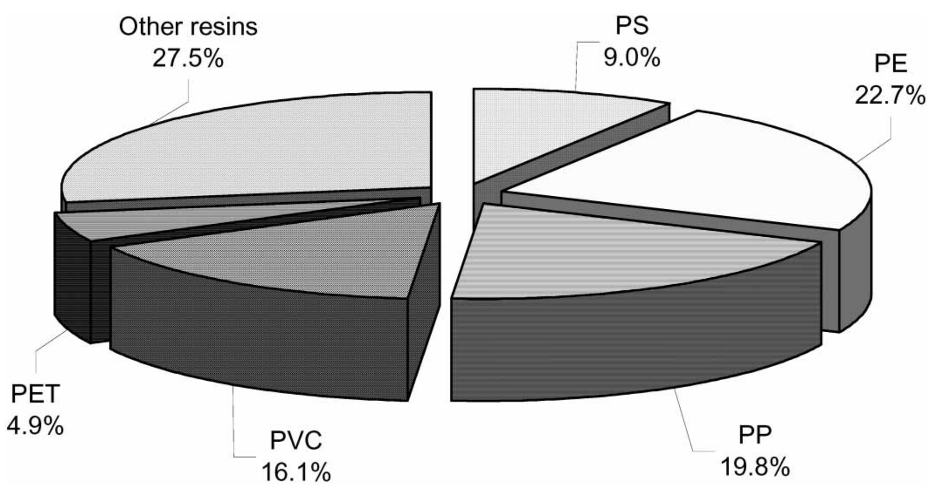

FIGURE 4 Breakdown of plastic production (1.36×10^7 tonnes) by resin type, in Japan (FY 2001) [3]. *Note*: production of PET is 0.066×10^7 tonnes [4].

Many kinds of plastics are in wide use today. Table I lists the main types of resins in use and their utilization. Moreover, breakdowns of plastic production, and plastic waste by resin type are shown in Figs. 4 and 5, respectively. Figure 4 shows that PE, and PP represent the largest volumes of commodity plastics, which are mainly used in packaging the industry (Table I), followed by PVC with 16.1% [3,4]. Meanwhile,

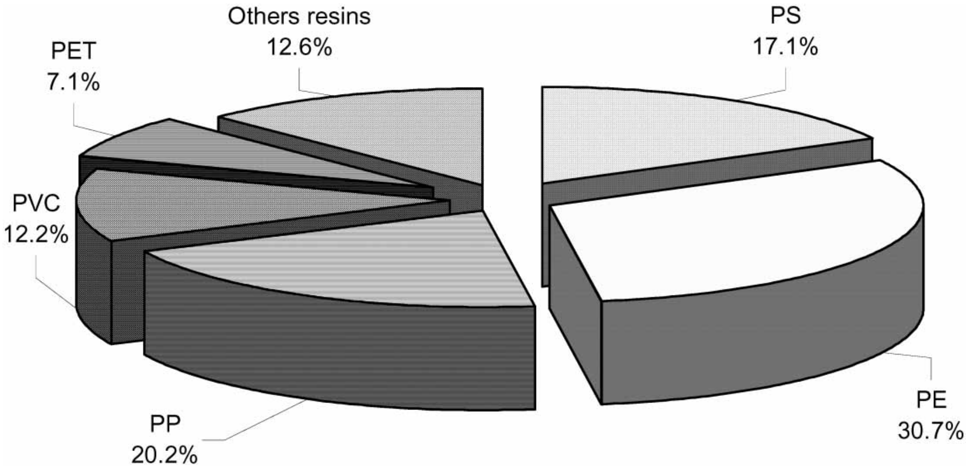

FIGURE 5 Breakdown of plastic waste discharge (0.99×10^7 tonnes) by resin type, in Japan (FY 2000) [1]. *Note*: the amount of waste PET is determined on the basis of the consumed amount, i.e. approximately 0.07×10^7 tonnes [4].

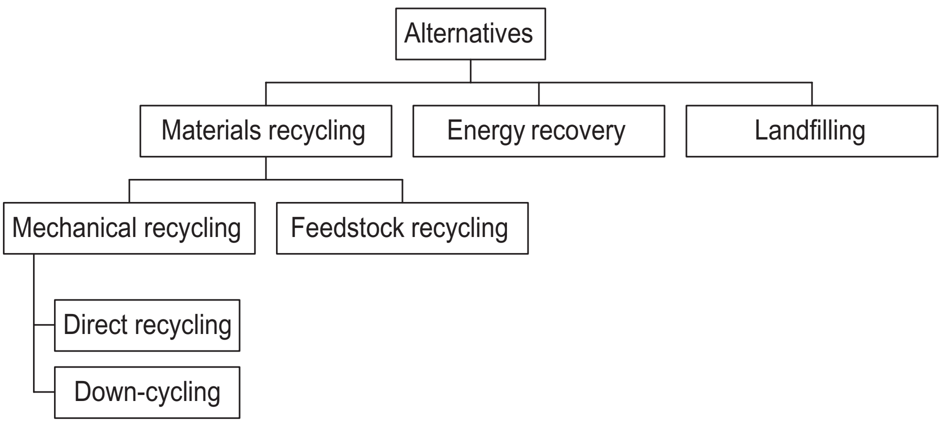

FIGURE 6 Alternatives for management of plastic wastes.

Fig. 5 shows that PE and PP are also the major sources of plastic waste, followed by PS and PVC with 17.1 and 12.2% respectively.

The growth of plastic waste has a negative impact on the environment. The potential reasons for this are that the available capacity for landfilling of wastes is declining and the incineration of plastics may cause the emission of harmful gases, together with generation of toxic fly and bottom ash that contain lead and cadmium [5].

In the view of the formation of a recycling-oriented society, several alternatives, with their specific advantages and disadvantages, are being considered for the control plastic wastes. At present, there are three main alternatives for the management of plastic wastes in addition to landfilling, as shown in Fig. 6:

(1) Mechanical recycling: the method by which waste plastics are recycled into new resources without affecting the basic structure of the material. It includes: (a) direct recycling to virgin plastic (i.e. high value end-product). It is the method for

reprocessing separated plastic waste into the same or similar type of end product; and (b) down-cycling (i.e. low value end-product). It is the method for producing low quality plastics products where finish and appearance are relatively unimportant.

(2) Feedstock recycling: the term feedstock recycling encompasses chemical recycling but is most often applied to a range of plastics recovery techniques that break down polymers into their constituent monomers, which in turn can be used again in refineries or petrochemical and chemical production. For example, pyrolysis and gasification processes have been developed to thermally degrade plastic waste, producing hydrocarbon fractions that may be used as a chemical feedstock or further refined into a fuel. In another example, the plastics are sometimes used as a direct replacement for petroleum in oil refineries, where the mixture of organic compounds produced by pyrolysis is then fractionated into purer, more valuable products [6].

(3) Energy recovery: the recycling method in which thermal energy is recovered from waste plastics. The option includes direct incineration with energy recovery, production of refuse derived fuel (RDF) and packaging derived fuel for incineration; or direct incineration as a fuel. Here, the energy content of the plastic is recovered at temperatures above 1450°C.

It is important to note that energy recovery, although an efficient alternative for the removal of plastic wastes, is the subject of great public concern due to the contribution of combustion gases to atmospheric pollution. Moreover, energy recovery is a consumptive recycling process (i.e. it turns the recycled material into energy rather than into usable material), and thus does not conform to the reuse-ratio requirement of the Japanese law on recycling [7]. On the contrary, mechanical recycling and feedstock recycling are closer to the ideal in that they produce materials that can be reused. Nevertheless, mechanical recycling requires high degree of sorting and separation. Feedstock recycling, on the other hand, appears as a potentially interesting approach. However, this method is expensive and relatively unproven, output market for pyrolysis oil is still under development and gas-cleaning issues are being researched. Of the two methods (i.e. mechanical recycling and feedstock recycling), mechanical recycling is especially effective because it uses less energy and has a smaller environmental impact than feedstock recycling [7]. In addition, capital investment requirements into feedstock recycling methods are much higher than requirements for mechanical recycling plants. Consequently, the mechanical recycling is favourable provided that via advanced separation technologies a high-quality recycling can be reached.

2. TECHNOLOGIES FOR SEPARATING PLASTICS

As the raw mixture usually includes various kinds of waste plastics, this makes the separation an important process that should be carried out prior to recycling. However, separation of mixed plastics encounters many problems (due to the characteristics of plastics) and represents one of the most problematic processes in the management system of plastic waste.

For example, it is difficult to distinguish shredded bottles of polyvinyl chloride (PVC) from shredded PET bottles. Despite that, the separation of PVC from PET should

TABLE II Required purity of sorted plastics for reuse [9].

Destination	*Required purity*
Reuse of plastics in circulating system as low quality plastics	> 95.0%
Reuse of plastics in circulating system as virgin plastics	> 99.5%
Reuse of plastics for agricultural, horticultural industry, etc.	> 99.0%
Use of plastics as oxidant in blast furnaces	< 1.0% (PVC impurity)

always be carried out in advance, as even a small concentration of PVC in a melt of PET can substantially decrease the quality of the whole batch. In another example, steel companies in Japan have recently planned to utilize waste plastics instead of fine coals for charging into blast furnaces. However, this leads to the question of the long-term furnace corrosion from increasing levels of PVC in waste plastics, since about two thirds of the chlorine produced from incineration of PVC appears as hydrochloric acid in flue gas with a reminder being retained by the ash [8]. Considering these examples, it is understandable why purchasers of plastics as secondary raw materials require that the mixed plastics be sorted properly (Table II) [9].

To deal with the problems that the plastics processing industry is facing, the research work is focused primarily on designing, developing and testing a variety of separation and sorting technologies able to recover valuable materials from wastes, which can be re-used or re-processed to form new products. In this regard, technologies developed in mineral processing can be of great help.

2.1. Wet Separating Techniques for Separating Plastics

One of the earliest publications on the separation of mixed plastics dates back to the early 1970s and originates from Japanese researchers that developed plastics flotation [10]. In 1976, Saitoh *et al.* [11] reported flotation of mixed plastics utilizing selective wetting characteristics in order to change the surface of specific plastics from hydrophobic to hydrophilic. Using this technique, plastics were collected with recovery higher than 95% and purity higher than 97%. Kounosu *et al.* [12] also studied flotation of plastics. Employing polyvinyl alcohol (PVA) of relatively low degree of polymerization, he reported a successful separation of PP from PE.

Later, Shibata *et al.* [13,14] successfully separated four different types of plastics, namely polyvinyl chloride (PVC), polycarbonate (PC), polyacetal (POM) and polyphenylene (PPE), using common wetting reagents like sodium ligninsulfonate, tannic acid, Aerosol OT and saponin. At first, floatability of individual plastics was measured by means of column flotation in the presence of various depressants, and a three-step process was then developed. The first step of the process involved heavy media separation to obtain a float product of PPE having purity and recovery of 100%, respectively. Subsequently, the PVC concentrate of 95.7% purity was separated by flotation during the second step using sodium lignin sulfonate depressant. Finally, the float product with 87.6% POM and the sink product with 90.3% PC were obtained at the third step of the process by means of flotation in the presence of a saponin/Aerosol OT combination. Meanwhile, Fraunholcz *et al.* [15] conducted several flotation experiments using different surfactants. His findings indicated that the absorption of depressants on plastics was mainly driven by hydrophobic interaction and electrostatic forces. Consequently, he suggested that adsorption-based wetting of plastics can be expected

with high-molecular-weight, i.e. macromolecular depressants. Moreover, Guern *et al.* [16] performed flotation of PVC/PET mixture after selecting suitable reagents. The selection of reagents was based on the studies of the behaviours of PVC and PET during grinding process using different type of mills, surface morphology after grinding, and surface chemistry. Separation of PET/PVC mixture was also reported by Drelich *et al.* [17], who demonstrated that by using froth flotation 95–100% recovery of PET or PVC can be achieved in separated products.

In 1997, Stuckrad *et al.* [18] developed a new dry-physical conditioning process by plasmaactivation of the plastic surface as an alternative to chemical conditioning. It was reported that this new conditioning method allowed the same sorting quality, but its emission of pollution was much lower. Furthermore, the results showed that by only one step of flotation, the purity of collected products was higher than 99% and the recovery was between 80–90%.

After reviewing the flotation of plastics [19] and discussing the relation of floatability of PVC and PMMA (polymethyl methacrylate) mixture with surface chemical related and gravity factors, Shen *et al.* [20] suggested that plastic flotation is a combination of froth flotation and gravity separation. Accordingly, the idea of particle control was applied for separation of mixed plastics. The experimental results showed that PVC and PMMA products were selectively separated by flotation. The recovery, and the purity of each collected product was higher than 98% respectively. Subsequently, they investigated the floatability of seven other types of plastics (including PVC, PET, PS and ABS) in the presence of methylcellulose and separated them into various groups. Accordingly, the results of flotation of plastics within the same group were limited, due to their small differences in floatability, whereas flotation of plastics of different groups was achieved with recovery generally higher than 99% and purity higher than 95% [21].

Pascoe *et al.* [22] also developed a method for separation of PVC and PET using flame treatment and flotation. Flame treatment was used to modify the surface of plastics to allow water-based coatings to be applied. The effect of the treatment was therefore to produce hydrophilic species on the surface of the plastics. The flame treatment involved the use of an acceleration chute that delivers the flakes through the flame of an angled burner. Then, a combination of a two-stage flotation process, and flame treatment was tested for the separation of PET. In the first stage, the PET was floated away from the PVC utilizing differences in particle thickness and surface contamination. The float product was then subjected to flame treatment and hydrophobic recovery prior to the second stage of flotation. In this stage, the PVC was reported to the float product leaving a PET-rich sink fraction. Nevertheless, it was reported that the efficiency of the process needs to be improved before being of commercial interest.

Italian researchers studied the wet density separation of different types of virgin plastics using a dynamic medium separation system. Plastic separation using this method required media with low density, say around 1000–1300 kg/m^3. For this purpose the most utilized media were: water and water solutions of calcium chlorite, sodium chlorite, calcium nitrate and ethyl alcohol. The process was tested on a PS/PP mixture using a two-stage Tri-Flo separator of 100 mm in diameter and water as medium (Fig. 7). The results were satisfactory as the PP content in the float products was 99.9% [23,24].

Moreover, the behaviour of PVC and PET in a LARCODEMS dense medium separator (Fig. 8) has been investigated using calcium chloride solutions as the medium [25]. It has been shown that particle thickness and surface conditioning can

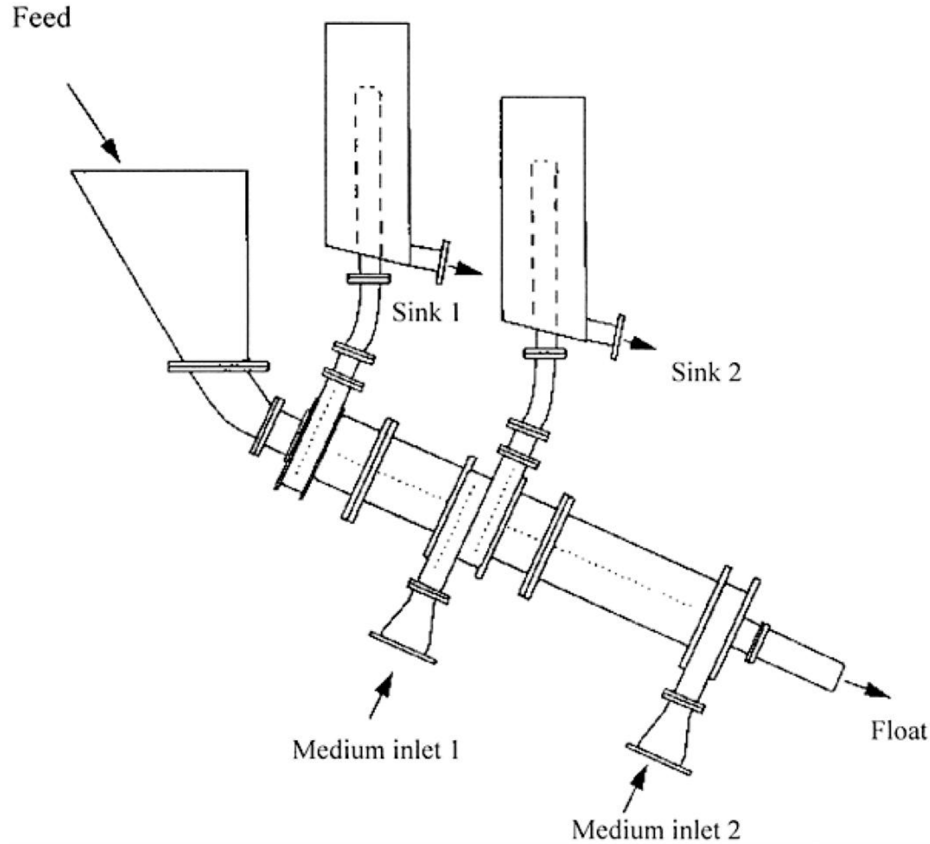

FIGURE 7 Schematic design of Tri-Flo separator.

have a significant influence on plastic behaviour within the separator. Thus, given the complexity of a mixture of shredded plastics in terms of size, shape and thickness, density separation using the LARCODEMS is likely to be only considered as a preconcentration step.

Tsunekawa *et al.* [26] employed a TACUB jig (Fig. 9) to separate plastics from scrap electric wires. Thus, he carried out separation of PVC from PE collecting products with purities higher than 98%. Based on the experimental results, he reported that the upstream speed and the amplitude of the pulsation of the water were the main parameters that influenced the efficiency of the separation process.

Furthermore, sink–float separation techniques are well-known wet methods for separation of mixed plastics. Shimoiizaka *et al.* [27] satisfactorily separated various mixtures of plastics of different densities by using a laboratory-scale sink–float separator. They reported that the impurity of each separated product was than 1%. Later, the separation of PET/PE and PET/PP mixtures was carried out in order to improve the purity of the raw input used in PET bottle recycling [28,29]. Initially, PET bottles and their caps (made of PE or PP) were shredded and the floatability of each polymer was tested. Since the results did not suggest that the required purity of PET plastic could be achieved by floatation (even with the addition of the wetting reagents dodecylamine acetate or polyvinyl alcohol), the mixtures were then processed in a sink–float process

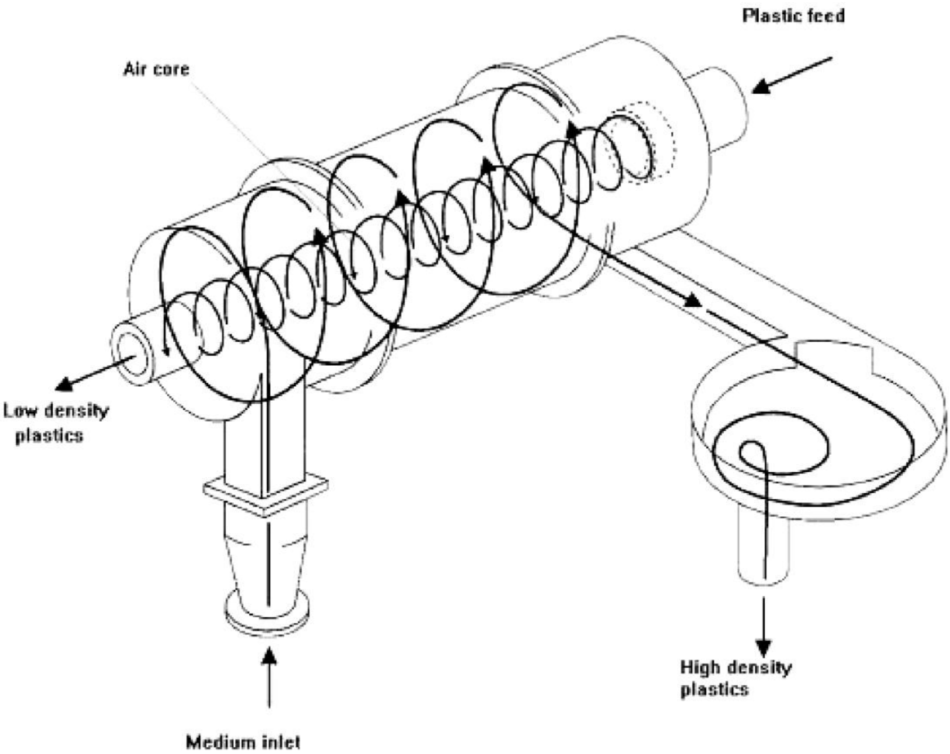

FIGURE 8 Diagram to illustrate the operation of a LARCODEMS separator.

using a drum-type sink–float separator. Finally, as the required purity of PET could not be obtained by either technique alone (i.e. neither flotation nor sink–float separation), a system utilizing a combination of the two processes was devised (Fig. 10). This system easily achieved the desired purity PET i.e. higher than 99.995%.

Although wet separation techniques provide adequate recoveries, they have clear disadvantages over dry ones, since some potential problems associated with wet separating methods in general, such as: (1) treatment of water from the process for reuse or discharge; (2) the requirement of expensive wetting reagents, and most importantly, and (3) dewatering or drying the mixture after separation cannot be avoided. In this regard, dry separation processes offer economical alternatives.

2.2. Dry Separating Techniques

In 1992, Dinger [30] conducted automatic sorting of PET and PVC plastic bottles utilizing a conveyor, resin/colour detector and air jet ejector. Conventionally, in the automatic plastics sorting system, it is common to use equipment applying near-infrared spectroscopic analysis with diffraction grating [31], acoust-optic tunable filter [32], or an optical filter [33]. Equipment applying Fourier transforming infrared spectrometry [34], Raman spectrometry [35] or infrared absorption using InGaAsP laser diode [36,37] are also used. Although these devices offer high accuracy, they are not always suitable for current sorting system from the viewpoint of cost-efficiency and handling [37].

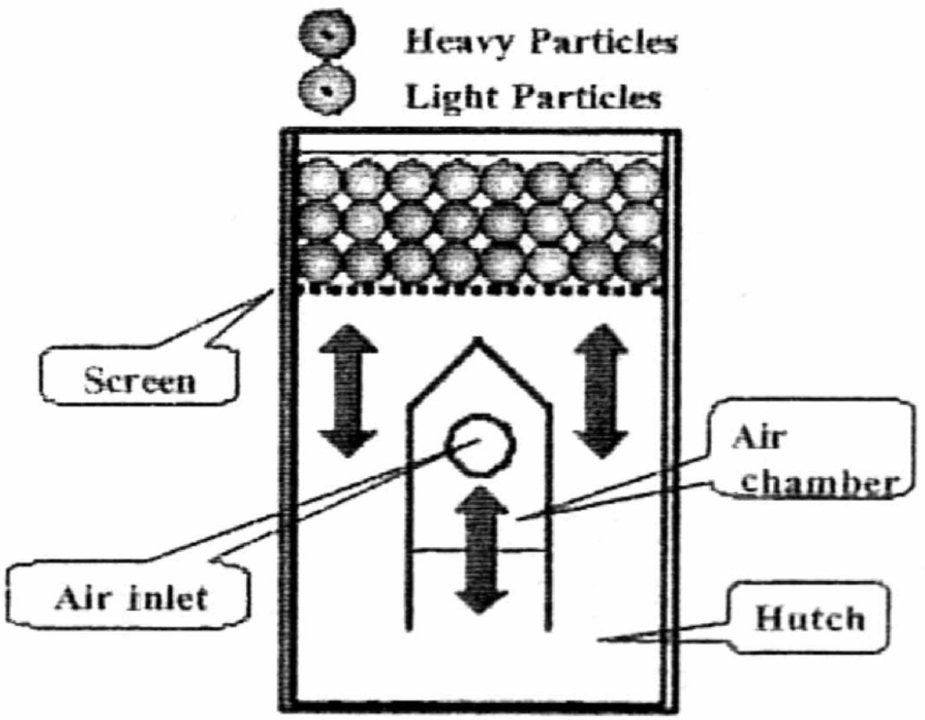

FIGURE 9 Schematic design of TACUB jig.

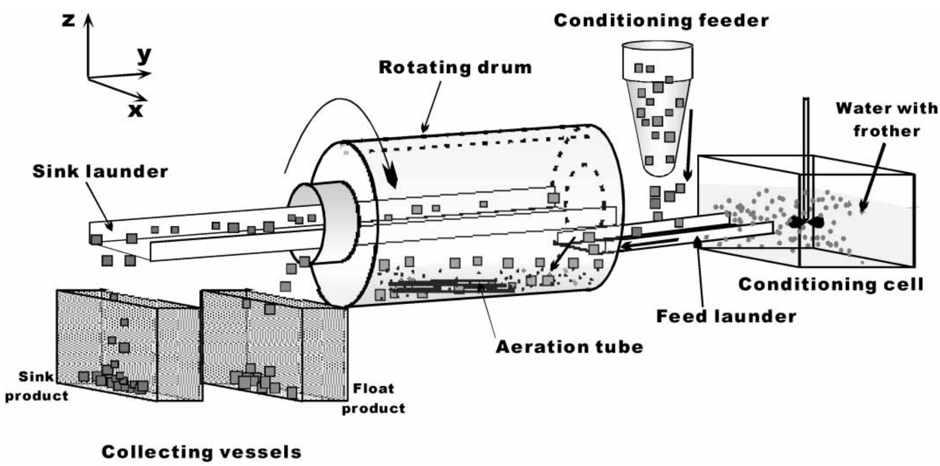

FIGURE 10 Schematic design of the drum separator that uses the combination of sink–float separation and flotation.

Generally speaking, dry gravity separation has the attraction of low capital input and operating cost which together with the lack of water, chemicals and drying requirements means it is environmentally friendly [38]. In the field of waste processing, if there is a difference in density between materials, vertical air classifiers have a history

of being very effective devices. Arai *et al.* [39] used a column-type air separator for dry separation of other plastics from PVC, which contains chlorine that damages incineration furnace. By using this technique, PVC product was collected with recovery generally higher than 80%. In 1999, Ito *et al.* [40] performed a feasibility study on separation of mixed plastics of different densities using a new type of pneumatic separator with acceleration–deceleration zones. Diskshaped plastics of PVC, PC and PP having thickness of around 2 mm and diameter of 10 mm were tested. Later, Nakajima *et al.* [41] carried out air separation of PET and PVC by taking advantage of different crushing resistance of two plastics. PET bottles and PVC sheet (thickness of 0.5 mm) were shredded to small pieces with a shear-type crusher. After crushing for 90 s, PET shreds, which were bent and twisted by the crush, were blown up (air flow rate of 3 m/s), whereas PVC shreds were collected as sink product, the recovery of collected products was 100%. However, the uses of air classifiers in the separation of mixed plastics are limited due to a small density differential between plastics to be processed.

Generally, vertical air classifiers are not considered to have a simple design [42], since they need to be connected with a device (commonly a cyclone) in order to subsequently separate the low-density fraction entrapped in the air stream from air (Fig. 11). Moreover, these air classifiers, which generally do not allow for separation into more than two fractions (known as extract and reject), require a large working space (because of their considerable height) and are not an answer where the space is at premium. With this in mind, Dodbiba *et al.* [44] investigated the performance of the air table when separating a PVC/PP mixture. The air table is more compact device with a simpler geometry (Fig. 12), since unlike the vertical air classifiers, it does not require separating the low-density fraction from the air stream and is capable of effectively treating plastics of different densities. Based on numerous tests, he reported that the purity of PVC

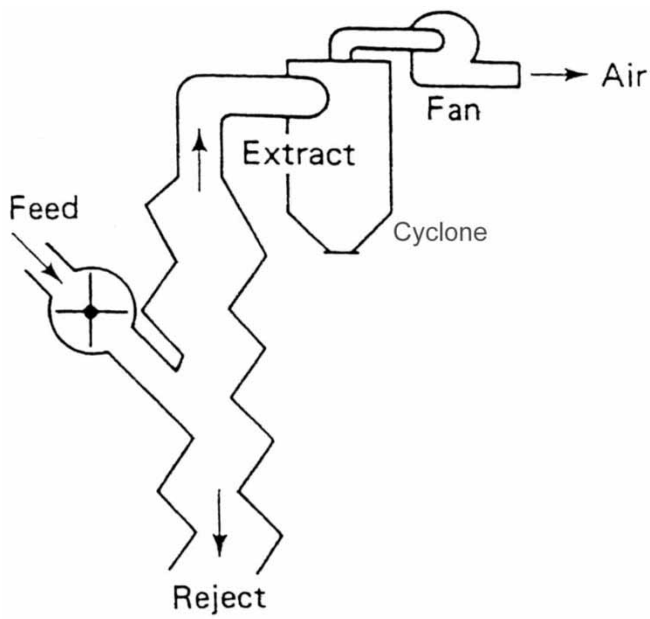

FIGURE 11 A basic arrangement for separation by zigzag air classifier [43].

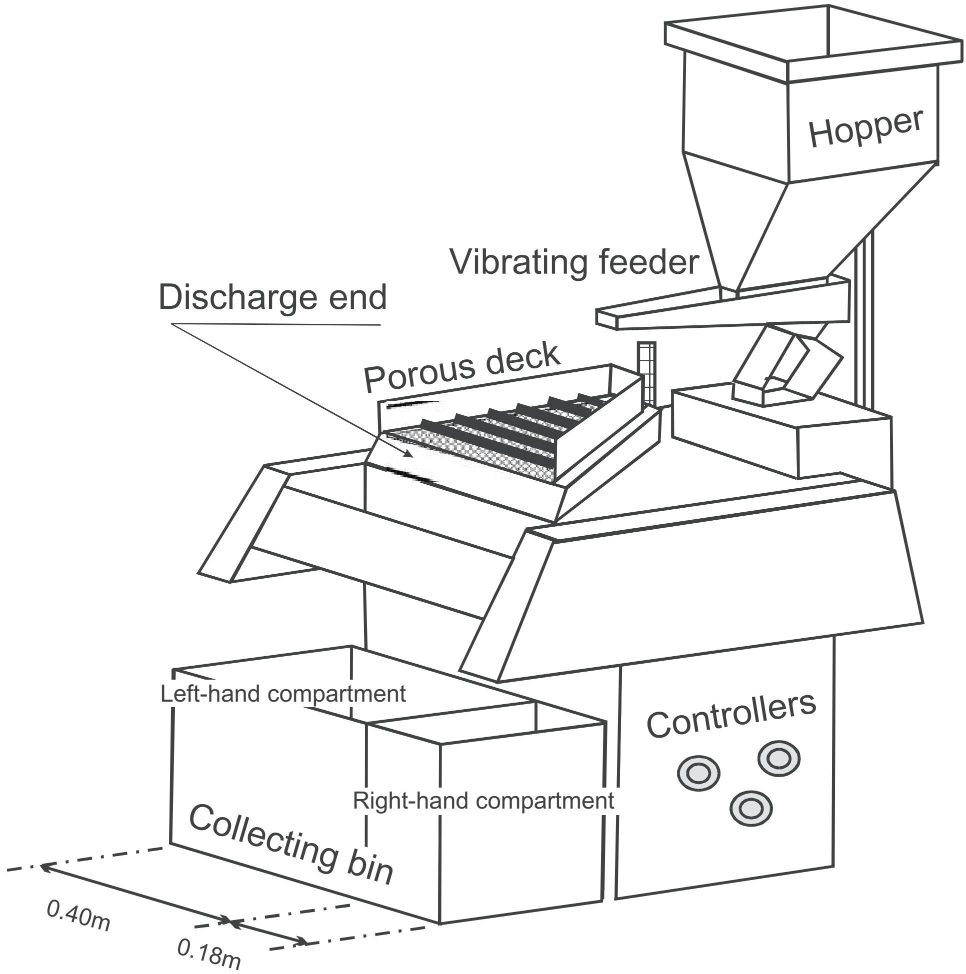

FIGURE 12 Schematic design of air table.

and PP products was 99.90% and 95.84% respectively, while the recoveries were higher than 96.70%.

Moreover, electrostatic separation by means of corona charging has been successfully applied to separate metal/non-metal mixtures, i.e. aluminium or copper from plastics or paper [45–49]. Furthermore, a technique that makes use of the eddy currents is also employed to separate plastic particles from a metal/plastic mixture [50,51]. However, these techniques are only applied to separate good conductors (such as metallic particles, etc.) from dielectrics, as they are unable to separate a mixture of dielectric particles such as mixed plastics.

Triboelectric separation (i.e. a kind of electrostatic separation that utilizes frictional charging) is the technique most frequently used to selectively separate two solid species of dielectric materials. Nevertheless, application of triboelectric separation of plastics is relatively new. One of the earliest publications on this subject dates back to the early 1990s and originates from Canadian researchers that developed a triboelectric fluidizing bed (Fig. 13) for separation of different binary plastic mixtures [52]. The experimental

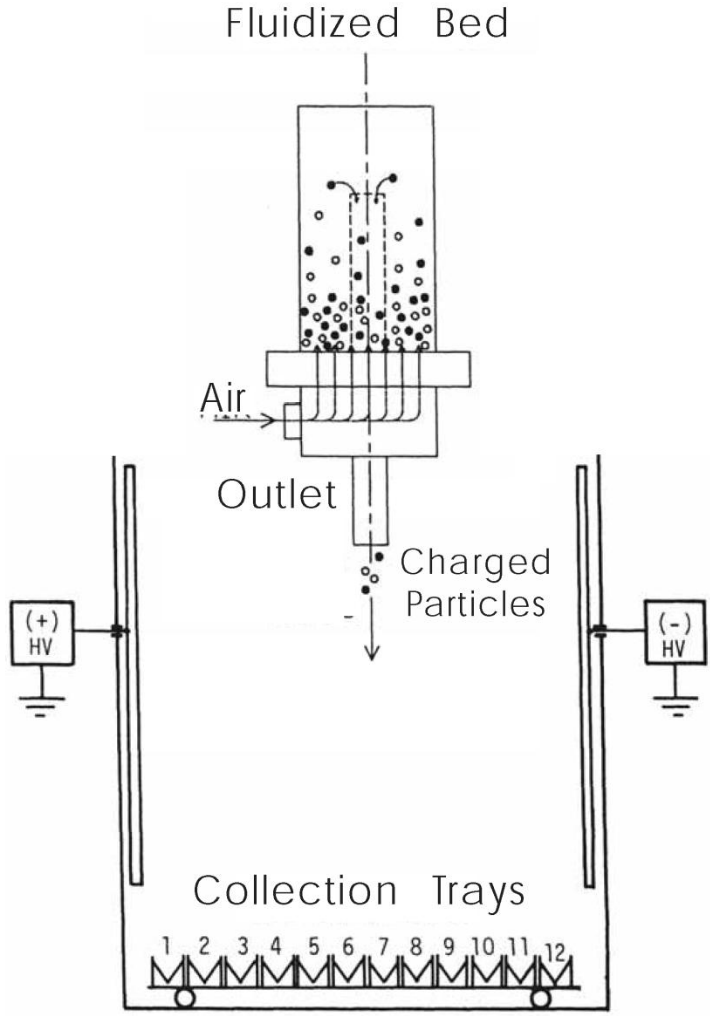

FIGURE 13 Fluidized bed triboelectric separator.

results showed an effective triboelectric separation of acrylic, nylon PE or PVC, achieving a purity of 95% or more. Later, triboelectric charging of plastics by vibrating chute (Fig. 14) was also reported [53,54]. Moreover, Matsushita *et al.* [56] triboelectrically sorted mixed plastics by means of a rotating drum (Fig. 15), which was comprised of a cylinder with rotary blades, whose form was adapted to enhance mutual friction between plastic pieces. He reported that a mixture of two kinds of plastics was successfully separated and the purity of products was not less than 90% (Matsushita *et al.*). Later, Takeshita *et al.* [58] devised a triboelectric separator for continuous separation of PVC sheets from other plastics. The apparatus consisted of a triboelectric section (which included two fluidized beds) and an electrostatic separating section. The mixture of plastic sheets was initially triboelectrified in the first fluidized bed and then introduced to the second one, where plastics were blown off into the electrostatic

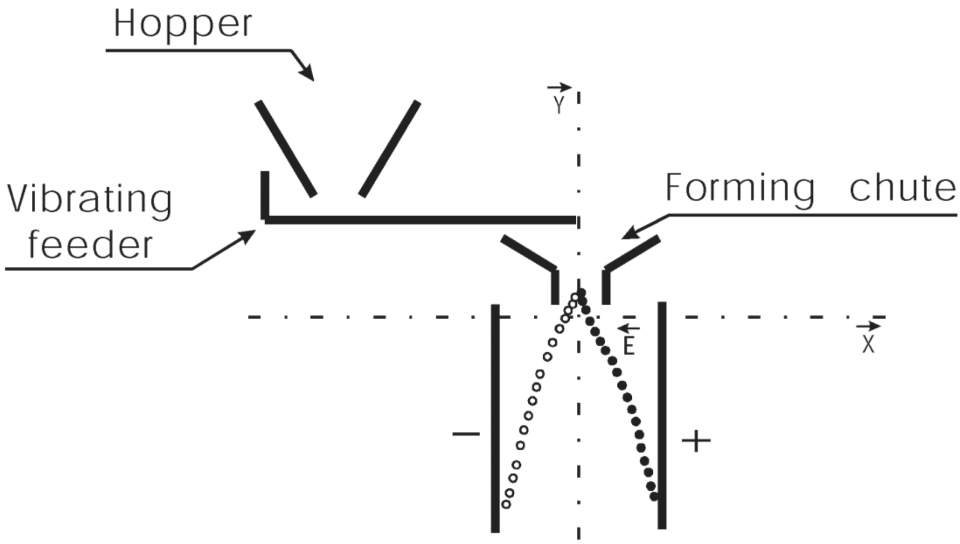

FIGURE 14 Vibrating chute triboelectric separator [55].

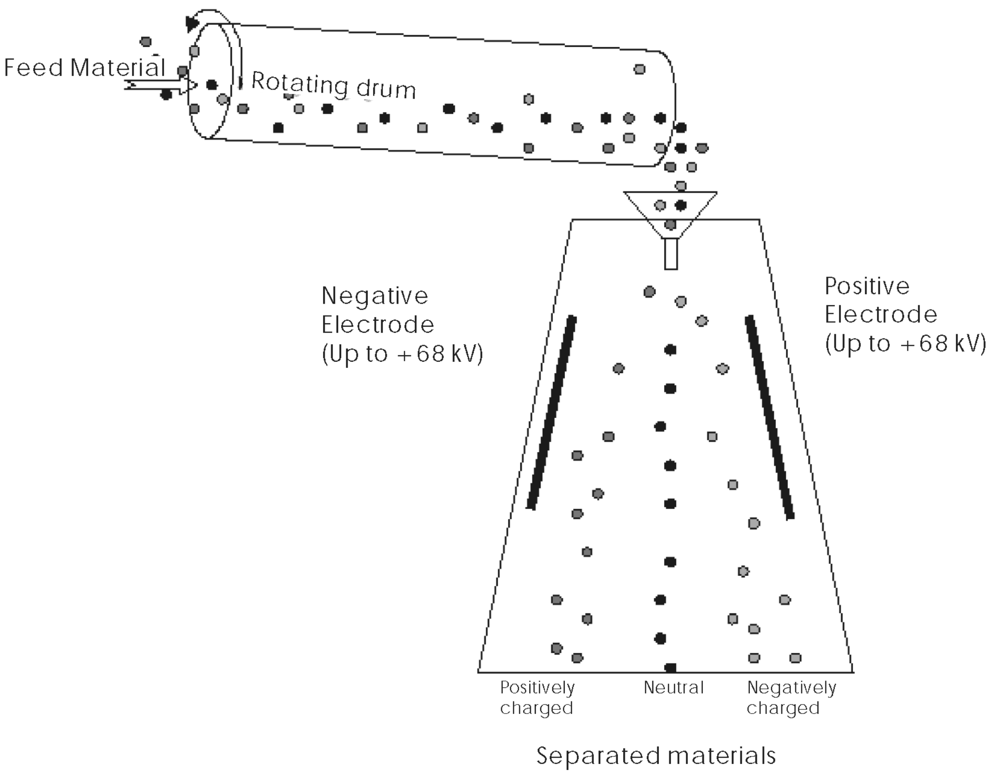

FIGURE 15 Rotating drum triboelectric separator [57].

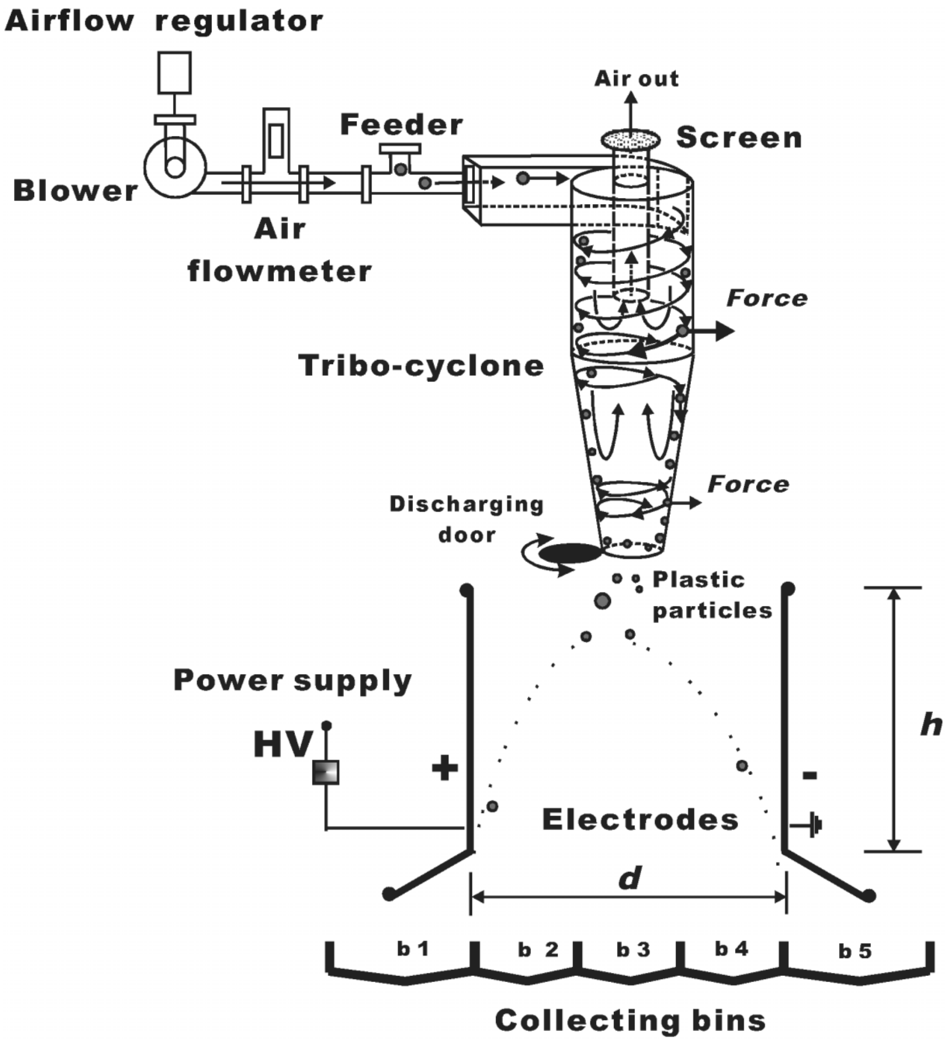

FIGURE 16 Schematic design of triboelectric cyclone separator.

separating unit (electric field strength of 150 kV/m). At the end of the process, the recovery and the purity of collected PVC product was higher than 70% and 90% respectively.

It can be noted that triboelectrification of mixed plastics is usually accomplished by one of the following charging devices: fluidized-bed (Fig. 13), vibrating chute (Fig. 14), or rotating drum (Fig. 15). As these devices tend to give rather low surface charge because the charging is primarily due to particle–particle contact, and the frictional speed is relatively low [59], Rodbiba *et al.* [60] employed an air cyclone as a charging device to produce a higher frictional speed. He developed a triboelectric cyclone separator (Fig. 16), which has been successfully tested in the laboratory for separating plastics. Considering his experimental results, the recovery of each collected product was higher than 75% while the purity was higher than 95%.

3. SUMMARY

An important subject in society is now to minimize the amount of plastic waste for environmental health or elongation of service life of disposal sites. As the raw mixture usually includes various kinds of waste plastics, this makes the separation an important process in terms of sustainable recycling.

To deal with the problems that the plastics processing industry is facing, the research work is focused primarily on designing, developing, and testing a variety of separation and sorting techniques able to recover plastics from wastes, which can be re-used or re-processed to form new products. In this regard, technologies developed in mineral processing can be of great help.

Various techniques for separating plastics materials have been recently developed. These techniques can be divided in two main categories, i.e. wet separating techniques and dry separating techniques. This paper presents the progress in separating plastics, reviewing the potential of the available techniques.

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